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(74) Agent: SCHOENMAKER, Maarten; Prof. Holstlaan 6, NL-5656 AA Eindhoven (NL).

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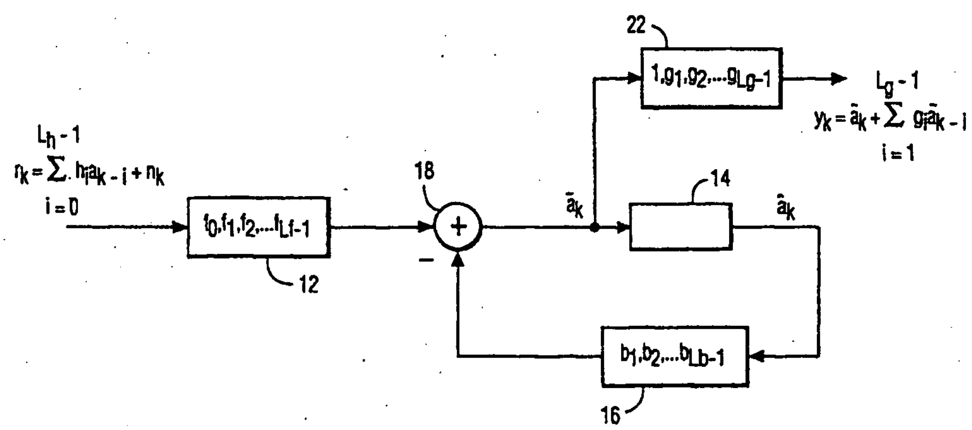
(54) Title: METHOD AND DEVICE FOR IMPROVING DFE PERFORMANCE IN A TRELLIS-CODED SYSTEM



(57) Abstract

A method and device for improving DFE performance in a trellis coded system by placing a short adaptive predictive filter after the DFE in order to whiten the error sequence at the output of the DFE.

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Method and device for improving DFE performance in a trellis-coded system.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention is directed in general to digital signal processing, and in particular to receiver based methods and devices for improving decision feedback equalizer ("DFE") performance in a trellis coded system.

2. Background of the Invention

In many digital communication scenarios (e.g. telephone transmission, broadcast TV transmission, cable etc.) The transmitted signal arrives at the receiver through more than one path in addition to the direct path. This condition is called "multipath" and leads to intersymbol interference ("ISI") in the digital symbol stream. This ISI is compensated for in the receiver through an equalizer which in many cases is a DFE as shown in Fig. 1. U.S. Patent No.5,572,262 shows one method of combating these multipaths.

A DFE 10 (Fig. 1) has two filter sections, a forward filter 12 and a feedback filter 16. The input to the forward filter 12 is the received data which includes the transmitted symbol sequence a_k, noise n_k and multipath h_i. The input to the feedback filter 16 is the quantized equalizer output $\hat{a}_k$. The output of both the sections are summed 18 to form the final equalizer output $\tilde{a}_k$ which is also the input to the next stage in a trellis-coded system, the trellis decoder. While a DFE performs better than a linear equalizer in severe ISI, the performance is limited by error propagation through the feedback filter 16 of the DFE 10. Error propagation occurs in the feedback filter 16 when the quantized equalizer output $\hat{a}_k$ is not the same as the transmitted symbol a_k. If an error is made in determining the symbol $\hat{a}_k$ at the output of the slicer 11, this incorrect symbol is fed back to the input of the feedback filter 16 and propagates. In many systems which employ error correction codes like trellis codes and/or Reed-Solomon codes to obtain very low error rates at moderate SNRs, the "raw" symbol error rate (SER) at the equalizer output can be extremely high. For example, in the VSB system, at threshold in white noise the SER at the equalizer output is about 0.2. The increased error propagation due to these high SERs can cause the DFE to lose a couple of dB in performance as compared to the case of no error propagation. Additionally, the error propagation causes

the error sequence at the equalizer output to be correlated, since it depends on past incorrect symbol decisions. This correlation has an adverse effect on the subsequent trellis decoder which is usually designed for a white noise sequence.

SUMMARY OF THE INVENTION

Accordingly, it is an object of the invention to reduce the mean-squared-error (MSE) and correlation of the DFE output error sequence. This object is achieved by placing a short adaptive predictor filter after the DFE in order to whiten the error sequence. The ISI introduced into the data symbol stream by this filter is then compensated in the trellis decoder by the use of delayed decision feedback sequence estimation (DDFSE) as described in "Delayed decision-feedback sequence estimation," by A. Duel-Hallen and C. Heegard, IEEE Trans. Commun., vol. COM-37, no. 5, pp. 428-436, May 1989.

The invention has applications in any trellis coded system that utilizes a DFE for equalization, especially in cases where the SER after the equalizer is high and error propagation causes problems. An example is terrestrial transmission of digital TV signals.

The invention can also be used in trellis coded systems with DFEs which are subject to colored noise interference. Again, the DFE cancels much of the interference but the adaptive predictor serves to whiten the noise further. This helps improve the trellis decoder performance.

The invention accordingly comprises the several steps and the relation of one or more of such steps with respect to each of the others, and the apparatus embodying features of construction, combinations of elements and arrangement of parts which are adapted to effect such steps, all as exemplified in the following detailed disclosure, and the scope of the invention will be indicated in the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the invention reference will be had to the following drawings:

Figure 1 shows a standard DFE;

Figure 2 shows a DFE in accordance with the invention; and

Figure 3 shows a DFE in accordance with the invention during a training sequence.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 1 is a diagram of the standard decision feedback equalizer 10 (DFE). The DFE includes a forward filter 12, a slicer 14, a feedback filter 16 and a subtractor 18. Let a_k be the transmitted trellis-coded symbol stream. The received signal r_k after multi-path distortion and added noise n_k can be written as

$$r_k = \sum_{i=0}^{L_h-1} h_i \, a_{k+d_h-i} + n_k \qquad (1)$$

where h_i, i=0... L_h-1 is the multipath channel of length l_h and delay d_h, and n_k is the additive noise which in general is neither gaussian nor white. The forward filter 12 is used to remove the pre echo or ghosts in the received signal. The slicer 14 quantizes the signal $\tilde{a}$ to the nearest symbol $\hat{a}_k$. If an error is made in this quantization the error is passed to the feedback filter 16 and remains in the system. The output of the feedback filter 16 is subtracted from the output of the forward filter 12 to provide $\tilde{a}_k$. $\tilde{a}_k$ is an estimate of the transmitted symbol a_k plus, an error e_k. It can also be expressed as:

$$^{a}{}_{k} = \sum_{i=0}^{L_f-1} f_i \, r_{k+d_f-i} + \sum_{i=1}^{L_b} b_i \, \acute{E}_{k-d_b-i} \qquad (2)$$

where f_i, i=0... L_f-1 are the forward equalizer taps, b_i, i=1... L_b are the feedback taps, d_f is the delay through the forward equalizer, d_b is the delay in the feedback equalizer and $\hat{a}_k$ is the constellation point closet to $\tilde{a}_k$. In the absence of error propagation, i.e. if $\hat{a}_k = a_k$, the error sequence e_k at the equalizer output 20 is white. However, in most cases the error propagation causes this error sequence to be correlated, that is, the noise samples are no longer independent. The "colored" noise affects the performance of a trellis coder, because a trellis coder is optimized for performance in a channel having all white guassian noise.

In accordance with the invention, as shown in Fig. 2, an adaptive filter 22 is placed at the output of the DFE 10 but before a trellis decoder (not shown). The output of filter 22 can be expressed as

$$y_k = {}^{a}{}_{k} + \sum_{i=1}^{L_g} g_i \, {}^{a}{}_{k-i} \qquad (3)$$

where $(1, g_1, g_2, g_3 \ldots g_{Lg})$ are the taps of the adaptive filter. Since $\tilde{a}_k = a_k + e_k$, then the adaptive filter output can be written as

$$y_k = a_k + \sum_{i=1}^{L_g} g_i \, a_{k+i} + e_k + \sum_{i=1}^{L_g} g_i \, e_{k-i} \qquad (4)$$

$$= a_k + \sum_{i=1}^{L_g} g_i \, a_{k+i} + e'_k$$

If the filter taps are chosen so as to minimize the variance of e'_k, the SNR of the sequence y_k can be improved. In addition, since e'_k is the prediction error sequence of the equalizer output error sequence e_k, it will be white see Widrow and Stearns, "Adaptive Signal Processing," (hereby incorporated by reference), at pages 99-116), which does not affect the performance of a trellis decoder.

Training of the Adaptive Filter

To minimize the error from the output of the DFE, or in other words to tune the adaptive filter taps g to the error e_k, the adaptive filter 22 is first placed through a training sequence as shown in Fig. 3. In many applications, such as digital TV, the training sequence is part of the transmitted signal. After the equalizer 10 has converged (via blind means, without using the signal a_k, or trained means which uses the signal a_k) the adaptive filter 22 receives a training sequence which is the difference between the output of the DFE $\tilde{a}_k$ and the transmitted symbol sequence a_k. This difference is the error e_k produced by the DFE.

$$\tilde{a} - a_k = e_k \tag{5}$$

This error sequence e_k is then input into the adaptive filter 22. The adaptive filter 22 forms an output sequence x_k as shown in Fig. 3, where

$$x_k = e_k + \sum_{i=1}^{L_g} g_i e_{k-i} \tag{6}$$

The filter taps g_k are adapted using the LMS algorithm as follows

$$\underline{g}(k+1) = \underline{g}(k) - \mu x_k \underline{e}(k) \tag{7}$$

where g = and $\underline{e}(k) = e_{k-1}, e_{k-2}, \ldots e_{k-Lg}]$. This adaptation adapts the filter taps to minimize the mean squared, error e_k^2, of the DFE.

Since the trellis decoder uses the taps $[g_1, g_2, \ldots g_{Lg}]$ in a feedback loop, error propagation can also occur hence it is also beneficial to limit the size of the taps g during adaptation, so that the trellis decoder that uses these taps does not suffer error propagation. If g is too small, however, the efficiency of the adaptive filter is reduced. Accordingly, an additional power constraint is imposed on the LMS algorithm to limit the amplitude of the taps which reduces the error propagation in the DDFSE trellis decoder (described next). A parameter P is chosen such that it is required that

$$\sum_{i=1}^{L_g} g_i^2 \leq P \tag{8}$$

At each step of the LMS algorithm this condition is tested, and if violated, the taps are rescaled appropriately.

The Adaptive Filter and DDFSE

Once the adaptive filter 22 is appropriately trained to minimize e_k, $\tilde{a}_k = a_k + e_k$ is input to the adaptive filter 22. The adaptive filter 22 although it has been trained to minimize e_k, it will also distort $\tilde{a}_k$. Equation 9 shows this distortion and represents the output of adaptive filter 22 as follows:

$$y_k = {}^{a}{}_{k} + \sum_{i=1}^{L_g} g_i\, {}^{a}{}_{k-i} \tag{9}$$

As stated above, if the filter taps g are chosen to minimize e_k, the SNR of the sequence y_k can be improved. y_k, however, is a distorted $\tilde{a}_k$ and includes the ISI introduced into the data stream by the adaptive filter 22. This distortion is then compensated for in the trellis decoder by use of delayed decision feedback sequence estimation (DDFSE)as described in A. Duel-Hallen and C. Heegard, "Delayed decision-feedback Sequence Estimation," IEEE Trans. Common., Vol. Com - 37, no. 5, pp. 428-436, May 1989, hereby incorporated by reference, and as summarized below.

From the definition of y_k, we see that an optimum trellis decoder which will remove the distortion of $\tilde{a}_k$, should minimize the metric (maximum likelihood decoding):

$$\sum_k \left[y_k - a_k - \sum_{i=1}^{Lg} g_i a_{k-i} \right]^2 \tag{10}$$

This equation, however, requires past symbol sequences a_{k-i} to be saved, and each tap g_i in the adaptive filter therefore introduces more memory into the system which causes the number of steps of a trellis decoder to grow exponentially with the number of taps in the adaptive filter 22. Therefore an expanded trellis is necessary to accommodate the memory (a_{k-i}) introduced by the adaptive filter 22.

A suboptimum, but computationally less intensive way of performing the trellis decoding is to instead minimize the following metric:

$$\sum_k \left[y_k - a_k - \sum_{i=1}^{Lg} g_i \acute{E}_{k-i,\,j} \right]^2 \tag{11}$$

where the sequence $\hat{a}_{k-i,j}$, i=1, ... L_g is the survivor symbol sequence associated with state j in the trellis. This scheme does not expand the number of states in the original trellis, but instead introduces decision-feedback in each of the trellis states. That is, since this scheme uses $\hat{a}_{k-i}$,

which is merely an estimate of, rather than the actual value a_{k-i}, there is no memory introduced into the system. Since there is no memory, an expanded trellis is not required, i.e. the number of states in the trellis remains the same even with the additional adaptive filter 22.

There is the possibility of error propagation in this implementation and hence the precaution is taken in the LMS algorithm of limiting the amplitude of the filter taps. The optimum value of P will depend on the trellis code and application. In the United States HDTV example, simulation results indicate that a value of P=0.15 gives good performance.

It will thus be seen that the objects set forth above, among those made apparent from the preceding description, are efficiently attained and, since certain changes may be made in carrying out the above method and in the construction set forth without departing from the spirit and scope of the invention, it is intended that all matter contained in the above description and shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

CLAIMS:

1. A decision feedback equalizer, (DFE) comprising:

an input which receives an input signal comprising, a transmitted symbol stream, noise and multipath;

a DFE output which provides a DFE output signal ($\tilde{a}_k$);

a forward filter (12) which filters the input signal;

a decision feedback loop comprising a subtractor (18), a slicer (14), and a feedback filter (16), wherein the subtractor (18) is coupled to both an output of the forward filter (12) and an output of the feedback filter (16) and subtracts the output of the feedback filter (16) from the output of the forward filter (12) to provide the DFE output signal ($\tilde{a}_k$) which is applied to an input of the slicer (14); and

an adaptive filter (22), coupled to the DFE output, to adaptively filter the DFE output, and whiten an error in the DFE output signal.

2. The DFE as claimed in claim 1, further including a training device which trains the adaptive filter to minimize the mean squared error in the DFE output.

3. A device for improving DFE performance, comprising:

an input which receives an output of a DFE;

an adaptive filter (22) having an adaptive filter input and an adaptive filter output, the adaptive filter input coupled to the input; and

an output coupled to the adaptive filter output for supplying an output signal to a DDFSE trellis decoder, which output signal is the DFE output signal with a smaller whiter error than the error in the output of the DFE.

4. The device as claimed in claim 3, wherein the adaptive filter (22) is adapted to receive a training sequence that adapts filter taps ($g_1 \ldots g_{lg-1}$) in the adaptive filter such that the adaptive filter (22) acts to whiten the error in the output of the DFE ($\tilde{a}_k$).

5. The device as claimed in claim 4, wherein the adaptive filter (22) further includes a LMS algorithm which is used to adapt the filter taps.

6. The device as claimed in claim 5, wherein the adaptive filter further includes a device for comparing

$$\sum_{i=1}^{L_g} g_i^2 \leq P \tag{11a}$$

where g_i is a filter tap and P is a power constraint imposed on the LMS algorithm to limit amplitude of the filter taps.

7. A method of improving DFE performance, comprising the steps of: receiving an output signal from the DFE which includes $\tilde{a}_k + e_k$;

adaptively filtering $\tilde{a}_k + e_k$;

providing the adaptively filtered $\tilde{a}_k + e_k$ to a DDFSE.

8. A method of decision feedback equalizing, comprising the steps of:

receiving an input signal comprising a plurality of symbols, noise and multipath;

forward filtering the received signal using a forward filter having a plurality of taps;

subtracting from the forward filtered signal a feedback filtered signal to provide a decision feedback output;

quantizing the decision feedback output to the nearest symbol to provide a quantized output;

feedback filtering the quantized output to provide the feedback-filtered signal; and

adaptively filtering the decision feedback output.

9. A DFE, comprising:

a forward filter (12), having an input which receives an input signal and a forward filter output;

a subtractor (18) having a first input coupled to the forward filter output and having a second input and a subtractor output;

a slicer (14)having an input coupled to the output of the subtractor and a slicer output;

a feedback filter (16) coupled to the slicer output and the second input of the subtractor; and

an adaptive filter (22) coupled to the output of the subtractor.

10. A television receiver, including a DFE, comprising:

a forward filter (12), having an input for receiving an input signal and a forward filter output;

a subtractor (18) having a first input coupled to the forward filter output and having a second input and a subtractor output;

a slicer (14) having an input coupled to the output of the subtractor and a slicer output;

a feedback filter (16) coupled to the slicer output and the second input of the subtractor;

an adaptive filter (22) having an input coupled to the output of the subtractor and an adaptive filter output; and

a DDFSE having an input coupled to an output of the adaptive filter.

11. A device for improving DFE performance, comprising:

DFE means (12,18,14,16) having an input and an output for providing a DFE output signal; and

adaptive filter means (22) coupled to the output of the DFE for adaptively filtering the DFE output signal and thereby whitening noise in the DFE output signal.

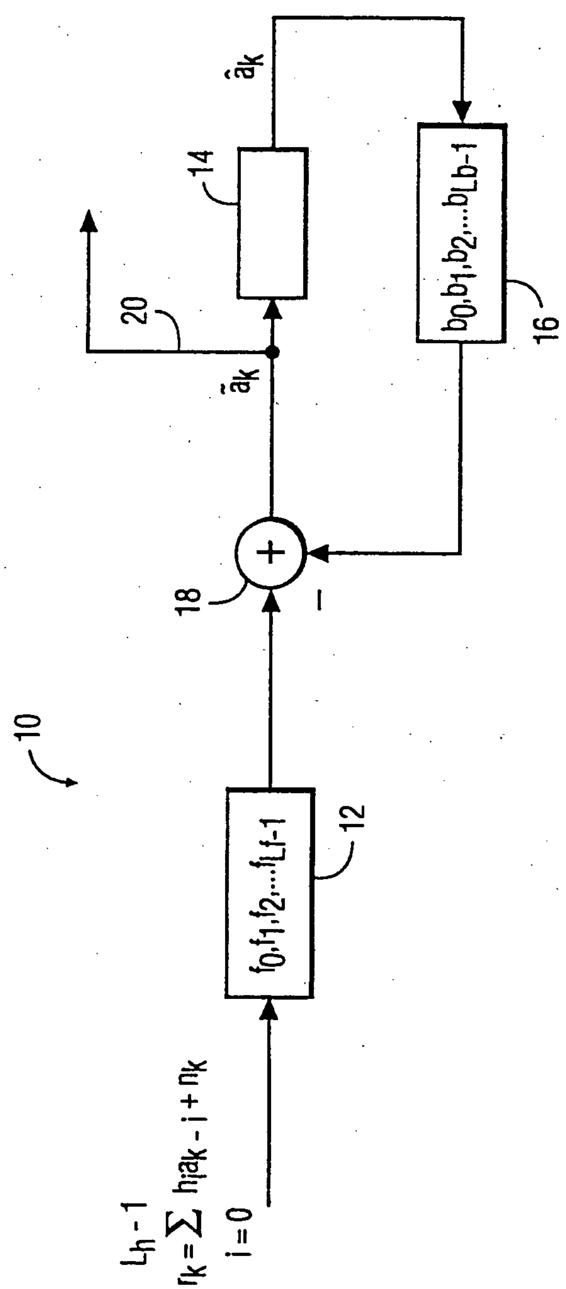
$r_k = \sum_{i=0}^{L_h-1} h_i a_{k-i} + n_k$
$f_0, f_1, f_2, \ldots f_{L_f-1}$
12
10
18
+
−
$\tilde{a}_k$
20
14
$\hat{a}_k$
$b_0, b_1, b_2, \ldots b_{L_b-1}$
16

FIG. 1

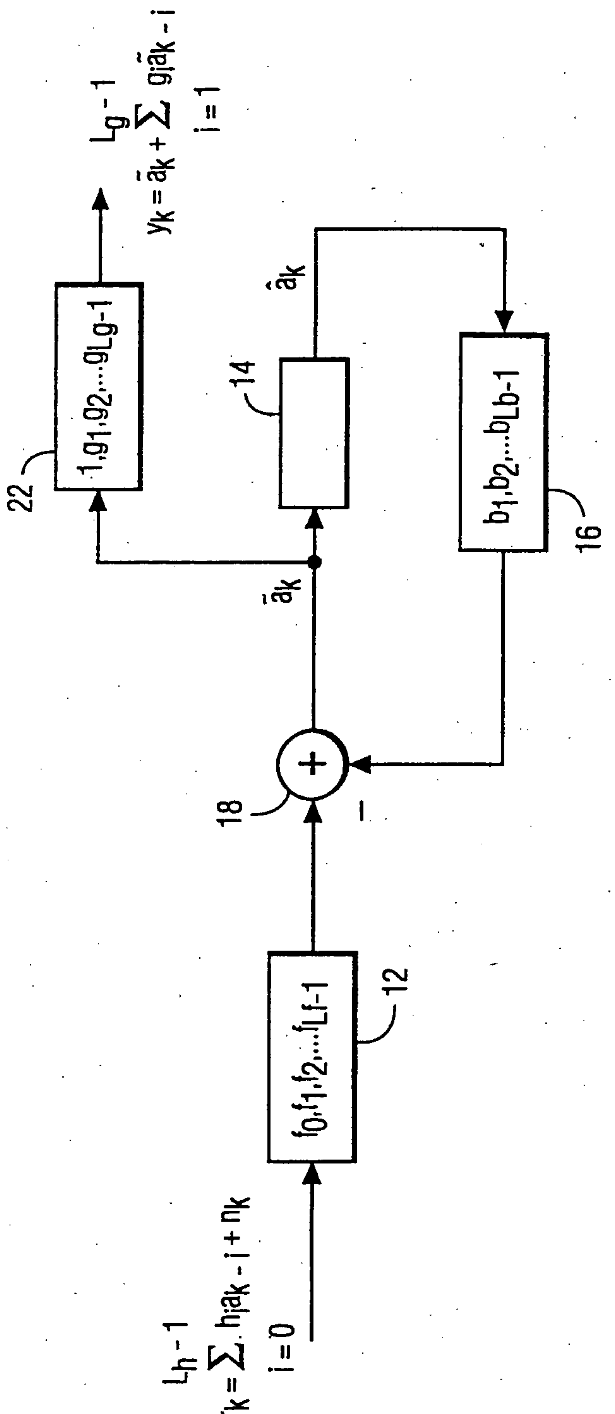
$y_k = \tilde{a}_k + \sum_{i=1}^{L_g-1} g_i \tilde{a}_{k-i}$
$1,g_1,g_2,\ldots g_{Lg-1}$
22
14
$\hat{a}_k$
$b_1,b_2,\ldots b_{Lb-1}$
16
$\tilde{a}_k$
18
+
−
$f_0,f_1,f_2,\ldots f_{Lf-1}$
12
$r_k = \sum_{i=0}^{L_h-1} h_i a_{k-i} + n_k$

FIG. 2

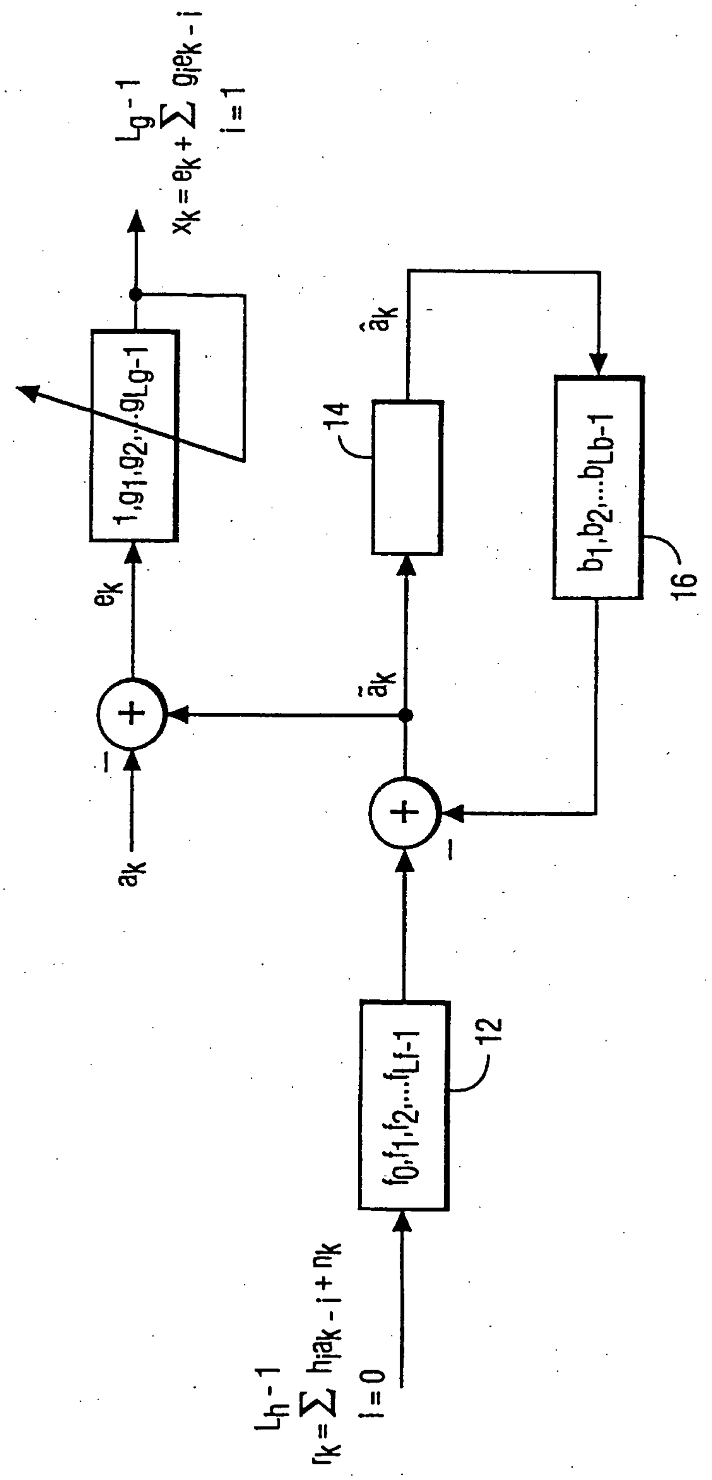
$x_k = e_k + \sum_{l=1}^{L_g-1} g_l e_{k-l}$
$1, g_1, g_2, \ldots g_{L_g-1}$
e_k
a_k
$\hat{a}_k$
14
$b_1, b_2, \ldots b_{L_b-1}$
16
$\tilde{a}_k$
$f_0, f_1, f_2, \ldots f_{L_f-1}$
12
$r_k = \sum_{l=0}^{L_h-1} h_l a_{k-l} + n_k$

FIG. 3

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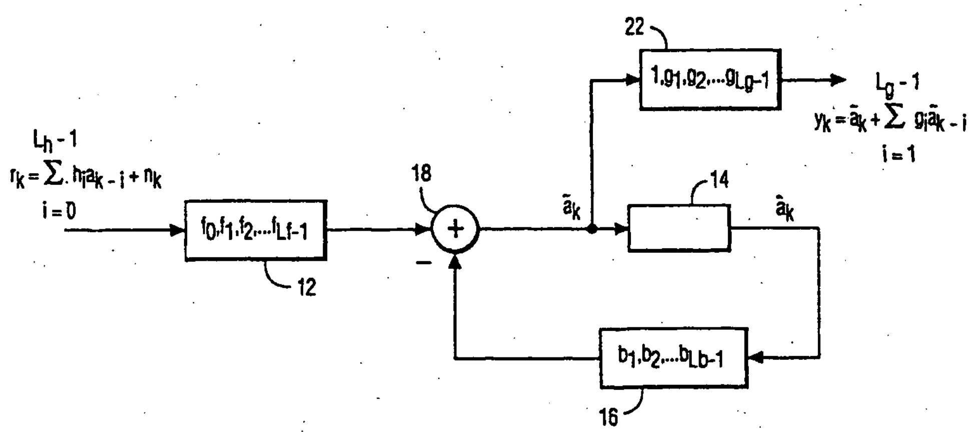

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/IB 99/01087

A. CLASSIFICATION OF SUBJECT MATTER

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According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

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IPC7: H04B, H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

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C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5742642 A (ANTONI FERTNER), 21 April 1998 (21.04.98), abstract --	1-11
A	EP 0707401 A2 (WANG, JIN-DER), 17 April 1996 (17.04.96), figures 2-3 --	1-11
A	US 5249200 A (MICHAEL CHEN ET AL), 28 Sept 1993 (28.09.93), column 7, line 64 - line 68; column 8, line 1 - line 5, figures 1,2C --	1-11
A	US 5909466 A (JOËL LABAT ET AL), 1 June 1999 (01.06.99), abstract --	1-11

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Date of the actual completion of the international search	Date of mailing of the international search report
24 January 2000	29 -01- 2000
Name and mailing address of the ISA/ Swedish Patent Office Box 5055, S-102 42 STOCKHOLM Facsimile No. +46 8 666 02 86	Authorized officer Rune Bengtsson/MN Telephone No. +46 8 782 25 00

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PCT/IB 99/01087

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